Major Extratropical Cyclones of the Northwest United States: 
Historical Review, Climatology, and Synoptic Environment

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Abstract

The northwest U.S. is frequently visited by strong midlatitude cyclones that can produce hurricane-force winds and extensive damage. This paper reviews these storms, beginning with a survey of the major events of the past century. A climatology of strong windstorms is presented for four areas from southern Oregon to northern Washington State and is used to create synoptic composites that show the large-scale evolution associated with such storms. A recent event, the Chanukah Eve Storm of December 2006, is described in detail, with particular attention given to the impact of the bent-back front and temporal changes in vertical stability and structure. The discussion section examines the general role of the bent-back trough, the interactions of such storms with terrain, the applicability of the “sting jet” conceptual model, as well as the relationship of central pressure to maximum winds. A conceptual model of the evolution of Northwest windstorm events is presented.
1. Introduction

Although the cool waters of the eastern Pacific prevent tropical cyclones from reaching the shores of the northwest U.S, this region often experiences powerful midlatitude cyclones, with the strongest possessing winds comparable to category two or three hurricanes. Such cyclones are generally larger than tropical storms and their effects are greatly enhanced by the region’s tall trees. Even though Northwest extratropical cyclones have produced widespread damage and injury, national media attention has been far less than for their tropical cousins. Only a handful has been described in the literature (Lynott and Cramer 1966, Reed 1980, Reed and Albright 1986, Kuo and Reed 1988, Steenburgh and Mass 1996), and questions remain regarding their mesoscale and dynamic evolutions, including interactions with terrain.

Reviewing the NOAA publication *Storm Data* and newspaper accounts, suggests a conservative estimate of damage and loss since 1950 due to cyclone-based windstorms over Oregon and Washington of 10 to 20 billion (2009) dollars. Perhaps the richest resource describing the powerful cyclones that strike the region is the extensive series of web pages produced by Wolf Read\(^2\), which reviews over fifty storms.

The Pacific Northwest is particularly vulnerable to strong cyclone-based windstorms due to its unique vegetation, climate, and terrain. The region’s tall trees, many reaching 30 to 60 m in height, act as force multipliers, with much of the damage to buildings and power lines not associated with direct wind damage, but with the impacts of falling trees. Strong winds, predominantly during major cyclones, account for 80% of regional tree mortality, rather than old age or disease (Kirk and Franklin 1992). Heavy precipitation in the autumn, which saturates Northwest soils by mid-November, enhances the damage potential, since saturated soils lose adhesion and the ability to hold tree roots. The substantial terrain of the Northwest produces large spatial gradients in wind speed, with enhanced ageostrophic flow near major barriers that produce localized areas of increased wind and damage. The most destructive winds from major

\(^2\) [http://www.climate.washington.edu/stormking/]
Northwest storms are overwhelmingly from the south and generally occur when a low center passes to the northwest or north of a location.

The closest analogs to major Northwest cyclones are probably the intense, and often rapidly developing, extratropical cyclones of the north Atlantic that move northeastward across the U.K. and northern Europe. Cyclones striking both regions develop over the eastern portion of a major ocean and thus exhibit the structural characteristics of oceanic cyclones, as documented by Shapiro and Keyser (1990). Several of the European events have been described in the literature, including the 15-16 October 1987 storm (Lorenc et al. 1988, Burt and Mansfield 1988), the Burns' Day Storm of 25 January 1990 (McCallum 1990), the Christmas Eve Storm of 24 December 1997 (Young and Grahame 1999), and the series of three storms that struck northern Europe in December 1999 (Ulbrick et al 2001). Browning 2004, Browning and Field (2004), and Clark, Browning and Wang (2005) present evidence that a limited area of strong winds associated with evaporative cooling and descent (termed a sting jet) occurred during the October 1987 storm. In the discussion section below, the characteristics of Northwest windstorms and the great extratropical cyclones of northern Europe are compared.

A major difference between the landfalling major cyclones of these two regions is the substantial coastal terrain of the Northwest, which contrasts to the lesser coastal topography of England and the European mainland. Several studies have examined the interactions between cyclones or other synoptic features and the coastal terrain of the Northwest. Ferber and Mass (1990) described the acceleration that occurs southwest of the Olympic Mountains as strong southerly flow produces a windward ridge on its southern flanks and a lee trough to its north, creating a hyper-pressure gradient over the coastal zone and near-shore waters. Steenburgh and Mass (1996) examined the interaction of the 1993 Inauguration Day Storm with Northwest terrain, finding little evidence of terrain-induced coastal acceleration but noting that troughing in the lee of the Olympics resulted in a several-hour extension of strong winds over Puget Sound.
Bond et al (1998) using flight level data from the NOAA P3 during the December 12, 1995 windstorm, found minimal coastal wind enhancement along the Oregon coast. Several papers (Loesher et al 2006, Olson et al 2007, Colle et al 2006, Overland et al. 1993, 1995) examined the barrier jets that develop seaward of the high coastal terrain of southern Alaska as low-pressure systems approached and crossed that coast. Major questions remain regarding storm-related coastal wind enhancement seaward of lower coastal terrain and how such enhancement varies with stability.

This paper documents the climatology of strong Pacific Northwest cyclones, examines the synoptic environments in which they develop, describes some intense events with large societal impacts, considers a well-simulated recent event (the 2006 Chanukah Eve storm), and identifies some outstanding scientific questions regarding their development and dynamics.

2. Historical Review

This section describes the general characteristics and societal impacts of a collection of strong midlatitude cyclones that have produced substantial damage and economic loss over the northwest U.S. The selection of these events is based on both objective evidence (such as surface wind speeds) and subjective information from newspaper articles, research papers, and weather-related publications such as NOAA’s Storm Data.

9 January 1880

The first documented Northwest windstorm occurred on 9 January 1880. Regarded by the Portland Oregonian as "the most violent storm ... since its occupation by white men", the cyclone swept through northern Oregon and southern Washington, toppling thousands of trees, some 2-3 m in diameter. Two ships off the central Oregon coast reported minimum pressures of 955 hPa as the cyclone passed nearby, and wind gusts along the coast were estimated at 120 kt. Sustained winds exceeding 50 kt began in Portland during the early afternoon, demolishing or unroofing many buildings, uprooting trees, felling telegraph wires, and killing one person.
Scores of structures throughout the Willamette Valley were destroyed and hundreds more, including large public buildings, were damaged.

*The Olympic Blowdown Storm of 29 January 1921*

The "Great Olympic Blowdown" of 29 January 1921 produced hurricane-force winds along the northern Oregon and Washington coastlines and an extraordinary loss of timber on the Olympic Peninsula. Over the southwest flanks of the Olympic Mountains more than 40% of the trees were blown down (Figure 1), with at least a 20% loss along the entire Olympic coastline (Day 1921). As noted in Ferber and Mass (1990) and discussed later in this paper, the localization of damaging winds probably resulted from pressure perturbations produced by the Olympics. An official report at the North Head Lighthouse, on the north side of the mouth of the Columbia River, indicated a sustained wind of 98 kt, with estimated gusts of 130 kt before the anemometer was blown away. Although the coastal bluff seaward of North Head may have accelerated the winds above those occurring over the nearby Pacific, the extensive loss of timber around the lighthouse and the adjacent Washington coast was consistent with a singular event. At Astoria, on the south side of the Columbia, there was an unofficial report of 113 kt gusts, while at Tatoosh Island, located at the northwest tip of Washington, the winds reached 96 kt.

*12 October 1962: The Columbus Day Storm*

By all accounts, the Columbus Day Storm was the most damaging windstorm to strike the Pacific Northwest in 150 years. It may, in fact, be the most powerful non-tropical storm to affect the continental U.S. during the past century. An extensive area stretching from northern California to southern British Columbia experienced hurricane-force winds, massive tree falls, and power outages. In Oregon and Washington, 46 died and 317 required hospitalization. Fifteen billion board feet of timber were downed, 53,000 homes were damaged, thousands of

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3 Before 1928, winds were measured by the Weather Bureau with a four-cup brass anemometer, compared to current three-cup anemometers. Thus, pre-1928 wind speeds are not strictly comparable to those reported for latter storms.

4 For example, Graham and Grumm (2007) found that the Columbia Day Storm had greater synoptic wind and geopotential anomalies than any other cyclone for the period 1948-2006.
utility poles were toppled, and the twin 520 ft steel towers that carried the main power lines of Portland were crumpled. At the height of the storm approximately one million homes lost power in the two states, with damage estimated at a quarter of a billion (1962) dollars.

The Columbus Day Storm began east of the Philippines as a tropical storm, Typhoon Freda, and followed the passage of a moderate storm the previous day. As it moved northeastward into the mid-Pacific on 8-10 October, the storm underwent extratropical transition. Twelve hundred miles west of Los Angeles, the storm abruptly turned northward and began deepening rapidly, reaching its lowest pressure (roughly 955 hPa) approximately 480 km southwest of Brookings, Oregon at around 1400 UTC 12 October 1962 (see Figure 2 for the storm track). Maintaining its intensity, the cyclone paralleled the coast for the next twelve hours, reached the Columbia River outlet at approximately 0000 UTC 13 October with a central pressure of 956 hPa, and crossed the northwest tip of the Olympic Peninsula six hours later (Figure 3a). At most locations, the strongest winds followed the passage of an occluded front that extended eastward from the storm's low center.

At the Cape Blanco Loran Station, sustained winds reached 130 kt with gusts to 179 kt, at the Naselle radar site in the coastal mountains of southwest Washington gusts hit 139 kt, and 130 kt (the instrument maximum) was observed repeatedly at Oregon's Mount Hebo Air Force Station on the central Oregon coast. The winds at these three locations were undoubtedly enhanced by local terrain features, but clearly were extraordinary. Away from the coast, winds gusted to 80 to 110 kt over the Willamette Valley and the Puget Sound basin. Strong winds were also observed over California, with sustained winds of 50-60 kt in the Central Valley and gusts of 104 kt at Mt. Tamalpais, just north of San Francisco.

Lynott and Cramer (1966) performed a detailed analysis of the storm, noting that during the period of strongest winds nearly geostrophic southerly flow aloft was oriented in the same direction as the acceleration associated with the north-south oriented low-level pressure gradient.
The strongest surface winds occurred when stability was reduced after passage of the occluded front, thus facilitating the vertical mixing of higher winds aloft down to the surface. They also noted that the particular track of the storm, paralleling the coast from northern California to Washington State, was conducive to widespread damage (Figure 2). The storm was poorly forecast, with no warning the previous day.

13-15 November 1981

A number of major Northwest windstorms have come in pairs or even triplets during periods of favorable long-wave structure over the eastern Pacific, and this period possessed such back-to-back windstorms, with the first producing the most serious losses. The initial low center followed a similar course to that of the Columbus Day Storm, except that it tracked about 140 km farther offshore, with landfall on central Vancouver Island (Figure 2). Over the eastern Pacific this storm intensified at an extraordinary rate, with the pressure dropping by approximately 50 hPa during the 24-hour period ending 0000 UTC 14 November 1981. At its peak over the eastern Pacific, the storm attained a central pressure of just under 950 hPa, making it one of the deepest Northwest storms of the century; coastal winds exceeded hurricane strength, with the Coast Guard air station at North Bend, Oregon reported a gust of 104 kt. Winds over the western Oregon and Washington interiors reached 60-70 kt.

Thirteen fatalities were directly related to the November 1981 storms: five in western Washington and eight in Oregon. Most were from falling trees, but four died in Coos Bay, Oregon during the first storm when a Coast Guard helicopter crashed while searching for a fishing vessel that had encountered 9 m waves and 70 kt winds. Extensive power outages hit the region with nearly a million homes in the dark.

Reed and Albright (1986) found that this cyclone was associated with a shallow frontal wave that amplified as it moved from the relatively stable environment of a long-wave ridge to the less stable environment of a long-wave trough. Both sensible and latent heat fluxes within
and in front of the storm prior to intensification contributed to the reduced stability. As with all major storms before 1990, the guidance by National Weather Service numerical models was unskillful, with the Limited-Area Fine Mesh Model (LFM) 24-h forecasts providing little hint of intensification. Kuo and Reed (1988) successfully simulated the 1981 storm using the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model, and found that roughly half the intensification in the control experiment could be ascribed to dry baroclinicity and the remainder to latent heat release and its interactions with the developing system. Their numerical experiments suggested that poor initialization was the predominant cause of the problematic operational forecast.

20 January 1993: The Inauguration Day Windstorm

Probably the third most damaging Northwest storm during the past 50 years (with the 1962 Columbus Day Storm being number one and the December 2006 storm in second place) struck the region on the inauguration day of President Bill Clinton. Winds of over 85 kt were observed at exposed sites in the coastal mountains and the Cascades, with speeds exceeding 70 kt along the coast and in the interior of western Washington. In Washington State six people died, approximately 870,000 customers lost power, 79 homes and 4 apartment buildings were destroyed, 581 dwellings sustained major damage, and insured damage was estimated at 159 million (1993) dollars.

The Inauguration Day Storm intensified rapidly in the day preceding landfall on the northern Washington coast. At 0000 UTC January 20th, the low-pressure center was approximately 1000 km east of the northern California coast with a central sea level pressure of 990 hPa. The storm then entered a period of rapid intensification, with the central pressure reaching its lowest value (976 hPa) at 1500 UTC on January 20th, when it was located immediately offshore of the outlet of the Columbia River (Figure 3b). A secondary trough of low pressure associated with the storm’s bent-back occlusion/warm front extended south of the
low center, and within this trough the horizontal pressure differences and associated winds were very large. During the next six hours, as the low-pressure center passed west and north of the Puget Sound area, the secondary trough moved northeastward across northwest Oregon and western Washington, bringing hurricane-force winds and considerable destruction.

Official National Weather Service forecasts were excellent for this storm, with the skillful predictions of this event reflecting, in part, the substantial improvement in numerical weather prediction during the previous ten years. Steenburgh and Mass (1996) investigated the effects of terrain on the storm winds using the PSU/NCAR mesoscale model. They found that pressure perturbations created by the interaction of the bent-back front with the Olympic Mountains extended the time period of high winds in the Puget Sound area but did not enhance peak winds.

12 December 1995

Of all the major windstorms to strike the Pacific Northwest, few were better forecast or studied more intensively than the event of December 12, 1995. Hurricane-force gusts and substantial damage covered a large area from San Francisco Bay to southern British Columbia, leaving five fatalities and over 200 million (1995) dollars damage in its wake. A number of locations in western Oregon and Washington experienced their lowest pressure on record as the storm’s low center bottomed out near 953 hPa off the Washington coast. The storm struck northern California early in the day, with gusts of 90 kt at San Francisco; later along the Oregon coast, from Cape Blanco to Astoria, winds gusted to 85 to 105 kt, while within the Willamette Valley and Puget Sound gusts approached 80 kt. Approximately 400,000 homes in Washington, 205,000 customers in Oregon, and 714,000 homes in northern California lost power during this storm.

A field program called COAST (Coastal Observation and Simulation with Topography Experiment) was underway during the December windstorm, and the National Oceanic and Atmospheric Administration (NOAA) WP-3D aircraft examined storm structure both offshore
and as the system approached the coastal mountains of Oregon and Washington. Flying offshore of the Oregon coast at around 1300 m, the plane experienced winds of 85-105 kt in a highly turbulent environment, with salt spray reaching the plane's windshield as high as 600 m above the wind-whipped seas (Bond et al. 1997).

14-15 December 2006: The Chanukah Eve Storm

The most damaging winds since the Columbus Day Storm of 1962 struck the region on December 14-15, 2006, with winds gusting to 80-90 kt along the Northwest coast, 60-70 kt over the western lowlands, and 85-105 kt over the Cascades. Over 1.5 million customers lost power in western Oregon and Washington, at least thirteen individuals lost their lives, and early estimates of damage ranged from 500 million to a billion (2006) dollars.

The December 2006 storm approached the region as a 970 hPa low and followed a more westerly trajectory than typical of major Northwest windstorms, which generally enter from the south to southwest (Figure 2). Intensifying as it approached the coast, the storm’s central pressure fell rapidly to approximately 973 hPa just prior to making landfall along the central coast of Vancouver Island. As the low-pressure center moved inland over southern British Columbia, the region of strongest pressure gradient and winds, associated with the bent-back trough on its southern flank, moved across western Washington, bringing widespread wind damage (Figure 3c).

Over western Washington, the damage associated with the 2006 storm substantially exceeded those of the 1993 Inauguration Day Storm. Nearly double the customers lost power than in 1993 and restoration took several weeks for some neighborhoods. Although the winds in 2006 were comparable to those of 1993, extraordinary wet antecedent conditions produced saturated soils and poor root adhesion, which resulted in substantially more tree loss and subsequent damage.

December 3-4, 2007
One of the region’s most unusual, long-lasting, and intense windstorms struck the northern Oregon and southern Washington coastal zones for an extended period on December 3-4, 2007. Two-minute sustained winds of 45 to 65 kt, with gusts as high as 130 kt, produced extensive tree falls, building damage, and power outages from Lincoln City, on the central Oregon coast, to Grays Harbor county of Washington. The extraordinary winds toppled or snapped off trees throughout coastal Oregon and Washington, including extensive swaths of forests (Figure 4). The December 2007 storm was highly localized: while winds were blowing at hurricane-force over the coastal zone, surface winds were light to moderate over Puget Sound and the Willamette Valley.

The December 2007 event was singular in several ways. First, most major Northwest windstorms are associated with intense and fast-moving low-pressure centers that move rapidly northward along the coast, producing strong winds for only three to six hours. In contrast, the long period of hurricane-force gusts from this windstorm was associated with a persistent area of large pressure gradient-- between a deep, slow-moving, low offshore and much higher pressure over the continent-- that remained over the north Oregon/southern Washington coastlines for nearly twenty-four hours (Figure 3d). Second, this storm was associated with extraordinary rainfall over the coastal mountains, with some locations in the Chehalis Hills of southwest Washington receiving 700 mm of rain in little over a day. In general, few cyclone-based windstorms are associated with sustained heavy rains and flooding, as found with this event.

3. Climatology of Windstorm Events

In this section, a climatology of major cyclone-related windstorm events is presented using an objective approach based on surface wind observations. Because most of the population in the region lives along the interior corridor west of the Cascade Mountains and east of the coastal terrain, this analysis will focus on identifying and characterizing strong southerly
wind events within that region. The wind climatologies at interior stations indicated that although most had their strongest winds from a southerly direction, some sites experience high winds from other directions due to regional terrain features such as gaps. For example, Portland, Oregon (PDX) reports a high frequency of strong winds from the east, the result of gap flow through the Columbia River Gorge (Sharp and Mass 2004). For most stations, the primary or secondary wind maxima are from a southeasterly to southwesterly direction, and these maxima are associated with the major cyclones that cross the region. Thus, to isolate cyclone-related high-wind events, the directions between 135 degrees and 225 degrees are used as a directional criterion. As a wind speed criterion, 35 kt was adopted since this speed represents the National Weather Service high-wind warning threshold. To aid in the identification of regional characteristics of such windstorm events, the region of interest was split into four sub-regions (Figure 5).

An event was identified as a major windstorm if two or more adjacent stations in a north-south line of ten stations (Figure 5) experienced 35 kt or greater sustained southerly winds in a 24-hour period. Using this criterion, thirty-two separate events were identified since 1948 (Table 1), all associated with Pacific cyclones. The largest number of events (18) occurred in the northernmost division (region 1) and the least (7) over the southern Oregon section (region 4). Interestingly, most of the events in the southern three regions occurred before 1965, compared to region 1, where only 22% of the events occurred before that date. Some events influenced more than one region, particularly the 1962 Columbus Day Storm, which affected all four.

The number of these cyclone-related windstorms peaks in December (Figure 6). Other major windstorm months include November, January and February, with reduced, but significant, numbers in October and March.

4. Synoptic Composites of Northwest Windstorms

An important question deals with the synoptic environment associated with major storms
and how that environment differs from climatology. To that end, composites of sea level pressure (SLP), 850 hPa temperature, and 500 hPa height for the dates of major windstorms noted above were created using the National Center for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) Reanalysis Project (NNRP) analyses. These data are at 2.5-degree spatial resolution and 6-h temporal resolution and are available from 1948 to the present. A daily climatological mean is calculated by interpolating monthly means, assuming they are valid for the mid-point of each month. The composites for each region were calculated for the time of strongest winds (0 hour) and for twenty-four and forty-eight hours before (-24 h, -48 h). In addition, anomalies from climatology and the areas in which the anomalies differ from the mean at the 95% and 99% confidence levels were calculated using a Student's t-test. In what follows, only the composites for region 2 are shown, the composites for the other regions are qualitatively similar, but with key features displaced to the north or south.

Turning to the region 2 sea level pressure composites, a large area of low pressure dominates the eastern Pacific two days before the high winds, with deviations from climatology approaching -14 hPa (Figure 7). During the subsequent 48h a trough over the southwestern portion of the domain rapidly moves northeastward and amplifies into a closed low, which is found just north of the region of high winds at the time of strongest winds (00h). The result is an intense north-south gradient over Washington and Oregon. There is relatively little variance over the region encompassing the low at the time of strongest winds, and the significance of the key trough/low center exceeds the 99% level.

At 500 hPa, a very broad, large-scale trough dominates the eastern Pacific two days before the strong winds (Figure 8). A short-wave trough rotates through this long-wave feature and approaches the Pacific Northwest at the time of strongest winds. Associated with this trough there is enhanced southwesterly flow over the eastern Pacific. The deviations from climatology of this trough exceed 250 m and are significant at the 99% level.
Significant deviations of 850 hPa temperatures from climatology accompany these windstorms (Figure 9). Two days before the strongest winds, an east-west zone of enhanced baroclinicity is found over the subtropical Pacific between a large cold anomaly over the north Pacific and a warm anomaly west of southern California. This cold anomaly, with a magnitude exceeding 6°C, moves towards the Pacific Northwest in association with a short-wave trough, while a warm anomaly pushes northward to the east. The significance of the cold anomaly exceeds the 99% level.


Since the Chanukah Eve Storm was extremely well forecast two days prior to the strongest winds, MM5 simulations were used to illustrate its synoptic and mesoscale evolutions. The strongest winds struck western Washington between 0600 and 1200 UTC 15 December 2006 and simulations initialized at 0000 UTC 14 December and 0000 UTC 15 December will be considered.

The 500 hPa geopotential heights from this storm are reminiscent of the composites, with a broad long-wave trough over the eastern Pacific and an intense short-wave trough moving northeastward toward the Northwest along an enhanced jet stream/height gradient (Figure 10). The 12-h sea level pressure forecast for 1200 UTC December 14 shows a large low pressure area over the eastern Pacific, with a low center of 988 hPa located 600 km west of the Oregon/Washington border (Fig. 11a). Twelve hours later, the low center had deepened to 978 hPa and had moved northeastward to 250 km west of the Washington coast. The strongest pressure gradient was found on the western side of the low associated with the bent-back warm front (Figure 11b). Switching to the 12-km domain, the three-hour pressure forecast for 0300 UTC December 15 (Fig. 11c) shows a 974 hPa low making landfall on central Vancouver Island, and an intense sea level pressure gradient associated with the bent-back trough and front.
During the next six hours, the low center moved northeastward into southern British Columbia, while the intense pressure gradient associated with the bent-back trough rotated into western Washington (Figs. 11d, e).

The simulated 10-m wind speeds and sea-level isobars during the hours leading up to landfall are shown in Figure 12. At 2100 UTC, when the low was still offshore, the strongest sustained winds, reaching 45 kt, were associated with the bent-back front to the northwest of the low center. At this and previous hours there was some suggestion of coastal acceleration along the Oregon coast and to a lesser degree southeast of the Olympics (Figure 12a). Six hours later the low has deepened to 972 hPa and sustained winds in the bent-back front and trough had increased to over 55 kt (Figure 12b). The coastal acceleration has disappeared, and as suggested later, this may be due to the destabilization of the atmosphere as cooler air moved in aloft. By 0600 UTC the strongest winds with the bent-back front were poised to make landfall as the low center began crossing central Vancouver Island (Fig. 12c). Finally, at 0900 UTC the extraordinary pressure gradient and winds with the bent-back trough had moved over western Washington (Fig. 12d). At the same time, the low center was moving over the British Columbia mainland to the north.

As noted by Von Ahn et al (2005, 2006), scatterometer winds are useful for determining the wind distributions in intense oceanic cyclones. The Quickscat scatterometer winds at approximately 1400 UTC December 14 indicate that the strongest sustained winds, reaching 50 kt or more, were associated with the warm front to the north of the cyclone and in the bent-back trough/front to the south of the low center (Fig. 13a). A latter view of the storm just before landfall (0400 UTC December 15) shows the strongest winds (exceeding 50 knots) to the south and southwest of the low center in the bent-back trough (Fig. 13b). Both of these scatterometer wind fields are consistent with the model simulations shown above, and reflect common structures in strong oceanic midlatitude cyclones.
A frequently observed feature of oceanic cyclones is an intense, bent-back front whose baroclinicity increases rapidly with height in the lowest few thousand feet above the ocean surface. Figure 14 shows the simulated 850 hPa thermal structures, heights, and winds for the storm before and during landfall. At 0000 UTC 15 December, an intense warm front extends west and north of the low center and splay out south of the low (Fig. 14a). As in cases documented by Shapiro and Keyser (1990) and Neiman et al. (1993a, b) the strongest winds are closely aligned with this bent-back baroclinic zone. During the period before the bent-back trough makes landfall, the intense bent-back temperature gradient and associated winds rotate around the low in counterclockwise fashion (Fig. 14b, c).

To explore the differences in conditions on the coast and within the western Washington interior, Figures 15 and 16 presents the temporal evolution of surface parameters at two sites: one immediately off the Pacific Coast (Destruction Island) and another over central Puget Sound (West Point lighthouse). At Destruction Island (15 km off the coast of the Olympic Peninsula), the winds increased rapidly and switched from easterly to southeasterly around 1800 UTC 14 December as the warm front pushed north of that location (Figure 15). Pressure continued to fall and winds generally increased after warm frontal passage and peaked at 31 ms$^{-1}$ (62 kt) around 0900 UTC 15 December after the passage of the bent-back front and trough. At West Point, inland between two main regional barriers (the Olympics and the Cascades), winds increased considerably later in the day during warm frontal passage between 2000 UTC 14 December and 0100 UTC 15 December. The winds during this period, constrained between the two barriers, maintained a southerly (roughly 200°) direction. The bent-back trough moved through between 0900 and 1000 UTC and was associated with the strongest gusts, reaching 27 ms$^{-1}$ (55 kt). At both sites, the strongest winds occurred during the period of rapid pressure rises and cold advection, a characteristic of most Northwest cyclonic windstorms.

A critical element of strong Northwest cyclone events is the evolution of the shear and
stability profiles aloft prior to and during the strongest winds. As first noted by Lynott and Cramer (1966), winds often increase rapidly during the transition to lower stability behind the occluded/warm fronts accompanying such windstorms. Figure 17 presents the wind and temperatures aloft over central Puget Sound based on ACARS (Aircraft Communications Addressing and Reporting System) data during ascents and descents into Seattle Tacoma and Boeing Field airports as well as surface observations at Seattle Tacoma Airport. Prior to warm/occluded frontal passage (1800-1900 UTC December 14), modest low-level winds were generally easterly and the lower atmosphere was stably stratified. The front crossed Puget Sound at approximately 0000 UTC 15 December, with a shift in the surface winds from southeasterly to southwesterly and a strengthening of the winds aloft. In the six hours after warm front passage (through 0600 UTC) the sounding became less stable and stronger winds progressively descended from aloft. The strong winds lowered up to the time of maximum wind gusts, near 0900 UTC.

A view of reflectivity and Doppler wind velocities from the National Weather Service Camano Island radar is found in Figure 18. Although the coastal zone is blocked by the Olympic Mountains, this radar gives a good view down the Strait of Juan de Fuca and over the interior lowlands. At 1934 UTC 14 December, a few hours prior to the passage of the surface warm front, moderate to heavy rain had spread over the region, and an “s-shaped” configuration of the zero-Doppler velocity line, characteristic of warm advection, was evident. Low-level winds were from the southeast at 10-30 knots. At 0054 UTC 15 December the warm front was moving through and the precipitation became more showery. An intense band of high reflectivity marks the surface front\(^5\). Low-level winds had shifted to southerly and increased to 50-60 kt, and slowly increased during the next four hours in the southerly post-frontal showers (0405 UTC). By 0806 UTC, the bent-back trough had reached the region and the winds had strengthened

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\(^5\) This band of very heavy precipitation resulted in intense rainfall, approaching 1 inch over an hour, to some locations. Extraordinary urban flooding occurred, including the drowning death of a woman in her basement.
As the trough moved through the Puget Sound region, strong westerlies began to push eastward into the Strait of Juan de Fuca (also evident in the radar). Convergence at the leading edge of the westerlies produced an area of greatly enhanced reflectivity. Finally, by 0959 UTC the bent-back trough had moved sufficiently eastward for strong westerly flow to push through the Strait into the northern Sound, with the leading edge of enhanced precipitation approaching the western Cascade slopes. Westerly winds aloft produced a north-sound line of rainshadowing east of the Olympics and the mountains of Vancouver Island.

6. Discussion

The above historical and climatological reviews of major cyclone-based windstorms affecting the Pacific Northwest interior reveal some of the essential synoptic characteristics of these events, while the case study of the Chanukah Eve storm illustrates important mesoscale features associated with such storms. In this section, mesoscale aspects will be discussed in more detail and some of the major outstanding questions are discussed.

a. The role of the bent-back trough and front

The simulations and mesoscale analyses of strong, recent Northwest cyclone/windstorms (e.g., Steenburgh and Mass 1996) reveal common structural elements. For example, for most events the largest temperature gradients above the boundary layer are in a bent-back front that passes through and south of the low. The strongest winds are on the cold side of this front, which is associated with the bent-back trough that extends south of the main low center. Structurally, this configuration is similar to those found in oceanic cyclones during major field programs such as ERICA and GALE (Neiman et al. 1993a, b) and is frequently evident in scatterometer winds over the oceans (Ahn et al., 2005, 2006; Figure 13 of this paper). As noted earlier, major oceanic cyclones have struck northern Europe and Great Britain, and the association of strong winds with the bent-back front and trough is evident both in observations and in realistic modeling studies (e.g., Clark et al 2005).
b. Interactions of storms with terrain

Unlike the situation in much of continental Europe and England, major Northwest windstorms interact with substantial coastal and near-coastal topographic barriers, with some terrain exceeding 2 km in vertical extent. Such interactions have the potential to greatly alter mesoscale pressure and wind distributions, and thus the impact of these storms. An important issue is the degree to which storm winds are accelerated by Northwest coastal terrain, which ranges from the relatively low, but extensive, coastal mountains of Oregon to the isolated, but higher, Olympic mountains.

Ferber and Mass (1990) showed that strong southerly or southeasterly winds interacting with the Olympic Mountains produces an intense pressure gradient on the southwest side of the mountains between the mesoscale pressure ridging to the south of the barrier and pressure troughing to the north (Figure 19). This enhanced pressure gradient often greatly accelerates winds along the central coast of the Olympic Peninsula during the initial periods of major windstorm events, and may well have contributed to the extensive blowdown along the central Olympic coastline during the severe 1921 event. Enhanced winds are also observed over northern Puget Sound and the eastern Strait of Juan de Fuca during such periods due to the hypergradient created by troughing to the lee (north) of the Olympics. Steenburgh and Mass (1996) examined the influence of local terrain on the winds associated with the Inauguration Day Storm of January 1993. Starting with a realistic high-resolution MM4 simulation, the coastal terrain was removed to determine its impact. The results suggested only minimal terrain enhancement of winds along the coast or over the Puget Sound interior, and that lee roughing due to the Olympics prolonged the period of high winds over the northern Sound.

Another obvious influence of regional terrain is the large ageostrophic component of the winds within and downstream of gaps and channels in the mountains prior to and during major cyclone-based windstorm events. As the low centers move northward or northeastward along the
coast, large east-west pressure gradients can develop across gaps in the Cascade and coastal mountains, resulting in strong downgradient flow, either associated with sea level gaps (such as the Columbia River Gorge) or higher-level gaps or passes, such as Stampede Gap of the central Washington Cascades, with the latter associated with hybrid gap/downslope winds (Steenburgh and Mass 1996, Mass and Albright 1985). Such downslope flow descending Stampede Gap has produced strong easterly or southeasterly winds reaching 70-120 kt prior to the development of strong southerly winds that occur as the low center makes landfall to the north. As a result, some lowland sites downstream of gaps can experience two wind maxima associated with cyclone-based windstorms: an initial easterly maximum when the low center is immediately offshore and a southerly peak when the low passes north of the region.

Strong ageostrophic flow up the major north-south “channels” west of the Cascade crest (such as the Willamette Valley, the Puget Sound basin, and the Strait of Georgia) is a hallmark of cyclone-based windstorms. As described by Overland (1984), when isobars are parallel to terrain barriers, the winds can be nearly geostrophic, but when the isobars are oriented normal to the mountain barrier crests so that there is a substantial along-barrier pressure gradient, air tends to accelerate downgradient ageostrophically within a Rossby radius of deformation of the terrain. In such situations, the Coriolis force is not an effective restraint on flow acceleration and the major balance is between pressure gradient and drag. It is partially for this reason that the greatest wind speeds in the interior lowlands occur when the low center moves north of the point in question, since that configuration produces a large along-barrier pressure gradient and ageostrophic acceleration at low levels. In addition, when a low center is northwest of a location, the winds aloft generally have a southerly component; thus, low-level ageostrophic acceleration to the north is supported by the downward mixing of southerly momentum from aloft. Furthermore, when a low center has moved northward, there is generally lower-tropospheric cold advection and destabilization, thus enhancing the downward mixing of higher
momentum air from aloft.

Bond and Walter (2002) and Bond et al. (1997) noted that winds measured at 600-1400 m ASL off central Oregon by the NOAA WP-3 aircraft during the December 12, 1995 windstorm did not evince any coastal acceleration as it made landfall to the north. During that period, the lower troposphere was well mixed with a high Froude number (roughly 3). In contrast, there is often substantial coastal acceleration when strong flow approaches the much higher terrain of southeast Alaska (Loesher et al 2006, Olson et al 2007, Colle et al 2006, Overland and Bond, 1993, 1995). Examining simulations of both the 2006 Chanukah Eve storm and a collection of landfalling storms during fall 2008, the authors have often noted coastal wind enhancement immediately upwind of the Oregon coastal terrain with landfalling cyclones, and that such enhancements are generally limited to periods of higher, pre-frontal, lower tropospheric stability.

To illustrate this enhancement, Figure 20 shows the near-surface winds every six hours from a realistic MM5 simulation of the 2006 Chanukah Eve storm using 4-km grid spacing. During the initial period, winds north of the warm front were southeasterly with no evidence of coastal acceleration (Figure 20a). There is a suggestion of coastal enhancement south of the warm front, where the winds had increased and shifted to southwesterly. Six hours later (1200 UTC, Figure 20b), the warm front had reached the Oregon/Washington border and coastal acceleration is evident, particularly north of Cape Blanco, on the southern Oregon coast. Six hours later, coastal enhancement was still apparent along the Oregon coast, but not along the Washington coast where the mountains are less continuous (Figure 20c). During the next twelve hours, as the low approached and cooler air began to move in aloft, the wind veered to a more westerly direction and the coastal enhancement weakened and subsequently disappeared (Figure 20 d, e).

To better understand the simulated coastal wind enhancement, the model soundings at Salem, Oregon, in the Willamette Valley, are shown in Figure 21. The initial sounding at 1200 UTC, immediately before surface warm frontal passage at that location, indicated an unsaturated
and stable boundary layer, with considerable shear between weak southeasterlies at low levels and moderate southwesterlies aloft (Figure 21a). Six hours later after warm frontal passage, the winds were southwesterly through depth, but considerable stability and shear remained in the lowest 100 hPa (Figure 21b). It is during this time that low-level coastal speed enhancement became apparent (Figure 21b). Over the next twelve hours low-level stability decreased as cooler air spread in aloft (Figures 21c,d). Simultaneously, coastal wind enhancements declined, either due to increased momentum mixing from aloft or lesser coastal blocking and jet formation. By 1200 UTC December, there is a deep adiabatic layer extending from just above the surface, with little evidence of coastal wind acceleration (Figures 21e). In short, when the lower atmosphere was characterized by onshore flow and considerable stability, coastal wind enhancement was evident. In contrast, during the period of strongest winds, a period with considerable destabilization aloft due to cold air advection, there is little suggestion of coastal wind enhancement along the Northwest coast. These findings are consistent with the aircraft observations taken during the 1995 windstorm (Bond et al 1997) in which no coastal enhancement was noted as the storm made landfall.

c. Application of the “sting jet” conceptual model to the northwest U.S.

As noted above, a number of European researchers (e.g., Browning 2004, Browning and Field 2004, and Clark, Browning and Wang 2005) have suggested the importance of a “sting jet” mechanism in major cyclones whereby mesoscale areas of particularly strong winds are associated with evaporative cooling and descent. Specifically, they propose that the most damaging winds emanate from the evaporating tip of the hooked cloud head on the southern flank of the cyclone, with evaporative descent bringing high-momentum air down to the surface. Furthermore, they noted a banded structure in the hooked cloud field that they suggested was caused by slantwise convection.

There are reasons to question whether this mechanism is significant in Northwest
windstorms. First, away from terrain there is little evidence for mesoscale localization of high winds for most large windstorms, a fact supported by the radar imagery shown above for the recent Chanukah Eve storm. Second, both infrared and water-vapor satellite imagery for a collection of major windstorm events do not suggest the cloud geometry noted by Browning 2004 and others during the period of strongest winds, namely, strong winds downstream of an evaporating cloud edge (Figure 22). Furthermore, satellite imagery of Northwest storms provides little evidence of the transverse circulations that play a major role in the sting jet conceptual model. Finally, high-resolution simulations of Northwest windstorms (e.g., Steenburgh and Mass 1996) can produce realistic strong winds without any evidence of sting jet structures and dynamics. It is, of course, possible that this mechanism could occur over the Northwest, but at this point, there is little evidence of its importance.

d. Central pressure versus wind speed

Central pressure is a useful, but imperfect, measure of wind speed and damage associated with Northwest midlatitude cyclones for many reasons: storms vary in size; the environmental pressure fields differ among storms, leading to different pressure gradients; the speed of motion and vertical stability properties of storms vary, as do storm trajectories with respect to major terrain features. The major cyclone-based Northwest windstorms that produced extensive damage had central pressures as low as the mid-950s hPa to as high as approximately 980 hPa. To illustrate, Table 3 presents the central pressures at landfall of the strongest windstorms striking Region 2 (see Figure 4) since 1958. The greatest windstorm in terms of the extent and magnitude of strong winds (the 1962 Columbus Day Storm) possessed a very low central pressure (956 hPa), but so did lesser events (November 1981, December 1995). In contrast, extremely damaging contemporary storms (January 1993 and December 2006) had considerably higher central pressures (970s hPa). Clearly, factors other than central pressure are important, such as vertical stability, vertical shear in speed and direction, and the relative pressure of the
surrounding environment. Regarding the latter, if unusually high pressure is in place, than a modest low or a strong one well offshore can produce the strong pressure gradients associated with extreme winds. This situation occurred on December 3-4, 2007 when the contrast between unusually high pressure over land and a low-pressure system (ranging from 955 to 970 hPa) far offshore produced winds exceeding 100 kt along the northern Oregon and Washington coasts for nearly 24-hours. Figure 3d shows the sea-level pressure forecast from the MM5 mesoscale model near the height of the event (27 hr, valid at 15 UTC 3 December 2007). The warm front and associated trough associated with the offshore low had moved up the coast; between the offshore low center and a region of high pressure over California, a zone of intense pressure gradient was established from central Oregon northward into southwest Washington, resulting in sustained hurricane-forced winds. This event was unique; most cyclone-based wind events last 3-9 hr as a deep low passes through. Only this event resulted in destructive winds for 24-h or more.

e. A conceptual model of Northwest wind events

Most major northwest windstorm events caused by strong midlatitude cyclones can be divided into four stages (Figure 23). In this schematic evolution, we consider a wind event over western Washington, but the ideas are appropriate for most of the region west of the Cascade crest, by shifting the features north or south. As noted above, the vast majority of such storms are moving to the northeast as they approach the region and make landfall.

In the pre-frontal stage, the low center is well offshore and a warm front or warm-occlusion extends westward south of the area of interest (Fig. 23a). Isobars are oriented roughly north-south, cool air is in place over the region at low levels, and winds are light (generally southeasterly). Strong winds are often observed at the exits of gaps in the regional mountains barriers and extensive precipitation has spread over the region at this time. With warm frontal passage (Fig. 23b), low-level winds accelerate substantially and temperatures rise, with the
orientation of the isobars shifting to be less parallel to the north-south terrain. Thus, there is an increased pressure variation along the regional terrain barriers (which are generally oriented north-south) and an increase in a southerly ageostrophic wind component. After frontal passage precipitation becomes lighter and more showery in character, with vertical stability considerably lessened allowing more effective mixing of southerly momentum down to the surface. This downward momentum mixing is enhanced by the increasing southerly and southwesterly winds aloft at this stage. Winds at this stage often gust to 20-40 kt and some initial damage may be reported. The most damaging period of windstorm events occurs next as the bent-back trough south of the low center rotates into the region (Fig. 23c). Winds can increase to 40-100 kt, with the strongest gusts limited to a period of 3 to 6 h. As the bent-back trough and associated low center move to the northeast the winds shift to a westerly or northwesterly direction aloft and an increased east-west pressure gradient develops. For western Washington, the result is often a westerly surge down the Strait of Juan de Fuca, with winds reaching 30-60 kt. Finally, the fourth or termination stage of the event occurs as the low moves well inland to the northeast (Figure 23d).

f. Some remaining questions

Significant issues remain regarding the dynamics, evolution, and modeling of Northwest windstorm events. Many of the strongest storms are associated with large-magnitude isallobaric pressure couplets, some with intense post-low pressure rises. Are isallobaric wind effects significant considering the already highly ageostrophic nature of the low-level winds in this mountainous region? Other questions include whether the “sting jet” evaporative descent mechanism is ever significant in the Northwest, and the relative important of downward mixing of geostrophic momentum aloft compared to ageostrophic, down-gradient acceleration at lower elevations. Model simulations, even at very high resolution, often indicate winds to be too geostrophic near the surface; the origin of this problem, probably in current planetary boundary
layer parameterizations, needs to be identified and fixed.

7. Summary and Conclusions

Land-falling oceanic extratropical cyclones can bring strong, damaging winds to the Pacific Northwest that are comparable to those associated with hurricanes. Major windstorms of the region are generally associated with central pressures ranging from 955 to 980 hPa, although major wind events over limited areas have accompanied storms with higher pressures (980-995 hPa). The strongest winds generally occur when a strong northeastward-moving low passes poleward of a location. Northwest windstorms are most frequent from November through February; since 1948 thirty-two separate events have brought sustained and spatially extensive winds greater than 35 kt to the western Oregon and Washington interiors, with many more events along the coast. Roughly once a decade a storm brings hurricane-force winds to the Puget Sound lowlands or the Willamette Valley, while on the coast this is usually a yearly event. Major Northwest cyclones have resulted in tens of billions of damage and the loss of several hundred lives during the past sixty years; the Columbus Day Storm of October 12, 1962 was the most powerful Pacific cyclone to strike the region over the past one hundred fifty years, and was perhaps the most power midlatitude cyclone to affect the U.S in a century. The predictability of these events has improved dramatically; prior to 1990 few were accurately forecast a day ahead, while since that time, most storms have been well predicted by operational numerical models. An exception to this situation was the February 8, 2002 “Valley Surprise” event, which brought winds gusting to 80 mph in the southern Willamette Valley without any warning due to a major model failure.

The synoptic evolution of the major storms is generally characterized by an extensive long-wave trough over the eastern Pacific, in which an embedded short-wave trough moves northeastward into the region. For western Washington, the most intense events are associated
with intense lows moving across the northwest Olympic peninsula or the lower portion of Vancouver Island, while for Oregon events the low crosses Washington State.

The structure of most major landfalling storms resembles the ocean cyclones described by Shapiro and Keyser (1990) and others. A bent-back occlusion or warm front is evident and the strongest pressure gradients and winds are associated with a bent-back trough south of the low center. As the low approaches the coast, the winds are generally light and southeasterly in the cool air north of the front. As the front moves northward, the winds accelerate rapidly as the isobars change orientation, creating an along-barrier pressure gradient and ageostrophic acceleration to the north. Furthermore, the lessening of stability after frontal passage facilitates the downward mixing of momentum. Winds then increase further as the bent-back trough moves in.

Coastal acceleration associated with such systems appears limited to the early period of relatively high stability; once the front has passed there is little evidence of near-shore wind enhancement. Northwest windstorms appear to have structural and synoptic similarities to the intense storms that make landfall on England and France; however, there is little evidence to date of the “sting jet” phenomenon, whereby mesoscale areas of enhanced wind and damage are caused by evaporatively cooled downdrafts.

Acknowledgements

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Table 1: Major windstorm event times based on the four regions shown in Figure 5. Shown are the times of the strongest observed wind speeds exceeding 35 kt at two or more adjacent stations. Time is in UTC.

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Table 2: Major cyclones that crossed between the Olympic Mountains and central Vancouver Island

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Table 3: Central pressures at landfall of major windstorms for region two over the past 50 years

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<td>956 hPa</td>
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<td>956 hPa</td>
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<td>January 20, 1993:</td>
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<tr>
<td>December 12 1995:</td>
<td>954 hPa</td>
</tr>
<tr>
<td>December 15, 2006:</td>
<td>970 hPa</td>
</tr>
</tbody>
</table>
Figure Captions

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Figure 10. 500 hPa heights and vorticity (color shading, blue low-red high) at 1200 UTC 14 December (a), 0000 UTC (b) and 0600 UTC (c) 15 December 2006. Graphics from a MM5 simulation with 36-km grid spacing.

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Figure 15: Destruction Island surface observations from 1200 UTC 14 December through 0000 UTC December 2006.

Figure 16: Surface observations at West Point, Washington.

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Figure 22: Satellite imagery of major Northwest windstorms at the time of maximum winds over
greater Washington. 0900 UTC December 15, 2006 infrared (a) and water vapor (b) GOES
imagery. Infrared imagery at 1330 UTC March 3, 1999 (c) and 1800 UTC January 20, 1993 (d).
Figure 23: Major stages of a typical Northwest cyclone-based windstorm.